DOCUMENT RESUME

ED 174 971 CS 004 976

AUTHOR Massaro, Dominic W.; Taylor, Glen A.
TITLE Reading Ability and the Utilization of Orthographic Structure in Reading. Technical Report No. 515.
INSTITUTION Wisconsin Univ., Madison. Research and Development Center for Individualized Schooling.
SPONS AGENCY National Inst. of Education (DHEW), Washington, D.C.
PUB DATE Jul 79
GRANT OB-NIE-G-78-0217
NOTE 61p.

EDRS PRICE MF01/PC03 Plus Postage.
DESCRIPTORS Elementary Education; Higher Education; *Language Processing; Letters (Alphabet); *Orthographic Symbols; *Reading Ability; *Reading Processes; *Reading Research

ABSTRACT

Previous research has demonstrated that readers utilize orthographic structure in their perceptual recognition of letter strings. Two experiments were conducted to assess whether this utilization varied with reading ability. Anagrams of words were made to create strings that orthogonally combined high and low single letter positional frequency and regular and irregular orthographic structure. These strings and the original words were used as test stimuli in a target search task in which subjects indicated whether a given target letter appeared in the test string. In the first experiment, 19 good and 15 poor college readers showed equally large effects of orthographic structure on task accuracy. In the second experiment, involving 42 sixth grade readers and 14 college students, the poor sixth-grade readers showed a smaller effect of orthographic structure than did average or good sixth grade readers, and the college students benefited more from orthographic structure than did either sixth grade group. Post hoc correlations of measures of orthographic structure with reading ability revealed similar results. The results suggest that the utilization of orthographic structure is an important skill in reading and that differences in this skill might be partially responsible for differences in reading ability of relatively young readers. Although older readers appear to have mastered this skill, the cost of mastery may be partially responsible for deficits at other higher-order processing stages in reading. (Rules for selecting materials used in the experiments and the test stimuli are appended.) (Author/FL)

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ED174971

Technical Report No. 515

READING ABILITY AND THE UTILIZATION OF ORTHOGRAPHIC STRUCTURE IN READING

by

Dominic W. Massaro and Glen A. Taylor

Report from the Project on
Studies in Language: Reading and Communication

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CS504976

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Madison, Wisconsin

July 1979

Published by the Wisconsin Research and Development Center for Individualized Schooling. The project presented or reported herein was performed pursuant to a grant from the National Institute of Education, Department of Health, Education, and Welfare. However, the opinions expressed herein do not necessarily reflect the position or policy of the National Institute of Education, and no official endorsement by the National Institute of Education should be inferred.

Center Grant No. OB-NIE-G-78-0217

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The Wisconsin Research and Development Center is supported with funds from the National Institute of Education and the University of Wisconsin.

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Table of Contents

	Page
List of Tables	vii
List of Figures	ix
Abstract	xi
Reading Difficulty	6
Feature Detection	6
Primary Recognition	7
Secondary Recognition	8
Rehearsal-recording	10
Long-term Knowledge, Verbal Ability, and Awareness	11
Orthographic Structure	12
Experiment 1	17
Method	17
Subjects	17
Stimulus List	19
Apparatus	20
Procedure	21
Results	22
Experiment 2	25
Method	25
Subjects	25
Stimuli Apparatus	25
Procedure	25
Results	26
Correlation Analyses	29
Discussion	32
Classroom Practice	34
Footnotes	42

Table of Contents (continued)

	Page
Reference Notes	43
References	45
List of Previous Reports	51
Appendix 1	53
Appendix 2	55

List of Tables

Table		Page
1	Mean and Range of Orthographic Structure Effects as a Function of Reader Group	28
2	Correlations of a Number of Predictor Variables with Overall Accuracy Performance as a Function of Reading Level in Experiments 1 and 2	31
3	The Most Frequently Occurring Consonant Clusters in Word-Initial and Word-Final Positions in English Words of Four Through Seven Letters	38

List of Figures

Figure		Page
1	An information-processing model of reading printed text.	3
2	Reaction times and percentage correct responses as a function of regularity and positional frequency for target and catch trials in the target search task (after Massaro, Venezky, & Taylor, 1979)	16
3	The five types of items and examples of each type used in the experiments	18
4	Percentage of correct responses for college readers as a function of the orthographic structure of the test string; reading ability is the curve parameter (Experiment 1).	23
5	Percentage of correct responses on target and catch trials for good and poor college readers as a function of orthographic structure of the test string (Experiment 1)	24
6	Percentage of correct responses for good, average, and poor sixth grade readers and for adult readers as a function of orthographic structure of the test string (Experiment 2)	27

Abstract

Previous research has demonstrated that readers utilize orthographic structure in their perceptual recognition of letter strings. Two experiments were carried out to assess whether this utilization of orthographic structure varies with reading ability. Anagrams of words were made to create strings that orthogonally combined high and low single letter positional frequency and regular and irregular orthographic structure. These strings and the original words were used as test stimuli in a target search task in which subjects indicated whether or not a given target letter appeared in the test string. In the first experiment, good and poor college readers showed equally large effects of orthographic structure on task accuracy. In the second experiment, poor sixth-grade readers showed a smaller effect of orthographic structure than did average or good sixth-grade readers. College sophomores benefited more than orthographic structure than did the sixth graders. Post hoc correlations of measures of orthographic structure with reading ability revealed similar results. The utilization of orthographic structure appears to be an important skill in reading and differences in this skill might be partially responsible for differences in reading ability of relatively young readers. Although older readers appear to have mastered this skill, the cost of mastery may be partially responsible for deficits at other higher-order processing stages in reading. To facilitate the teaching of orthographic structure, some of the important constraints in written English and various games for teaching these constraints are presented.

One of the primary concerns of educators is the wide range of reading ability across both child and adult populations. Good and poor readers have been shown to differ in performance on a variety of general tasks, but until recently little attempt has been made to explore how children of different reading abilities might differ in basic word recognition processes. If good and poor readers reveal fundamental differences in visual recognition processes, then remedial instruction in visual recognition for the poor readers would be required. The rationale for the present research is that the study of basic word recognition processes can aid in assessing word recognition abilities of good and poor readers at both the elementary school and adult levels.

The goal of the present research is to determine how good and poor readers evaluate and integrate two sources of information in the visual processing of letter strings. The most obvious source of information is the visual characteristics of the letters in the string. The second source involves the reader's knowledge of how letters are sequenced in the written language. Previous research (Massaro, Venezky, & Taylor, 1979) established the psychological reality of both of these sources of information and the present objective is to evaluate their contributions to letter processing as a function of reading ability. Before reporting the results of the present study, it is necessary to describe in some detail the processes involved in reading. The model for describing these processes is part of a more general language processing model we have developed and tested over the past few years (Massaro, 1975, 1978). Our concern in presenting this model is not to justify it over others but to provide a framework from which hypotheses about word recognition can be derived and tested.

The text in reading is a sequence of letters and spaces which conform to orthographic, syntactic, and semantic constraints defining the written language. The average English reader begins at the top left hand corner of the page and reads each line from left to right. A reader's eye movements are not continuous but occur in a series of short jumps called saccades. The fixation time between eye movements is roughly ten times longer than the movement time itself. In reading, an average eye movement of one to two degrees requires 20 to 30 msec, whereas fixation time averages 200 to 300 msec (Shebilske, 1975; Woodworth, 1938). Initial processing of the visual stimulus must occur during the fixation time since during the eye movement, light pattern is in flux and the processing time too short.

Figure 1 presents a schematic representation of the stages of processing in reading. During the fixation period the light pattern of the letters is transduced by the visual receptors. A feature detection process detects and transmits visual features to preperceptual visual storage. The features are described as visual because a direct relationship is assumed to exist between the stimulus properties of the letters and the information in preperceptual visual storage. The passive transduction of feature detection contrasts with the active construction of the following processing stages. There is no exact one-to-one relationship between the inputs and outputs of the following processing stages, since these stages actively utilize information stored in long-term memory in their transformations.

The primary recognition process attempts to synthesize the isolated features in preperceptual visual storage into a sequence of letters and spaces in synthesized visual memory. To do this, the primary recognition process can utilize information held in long-term memory, which for the

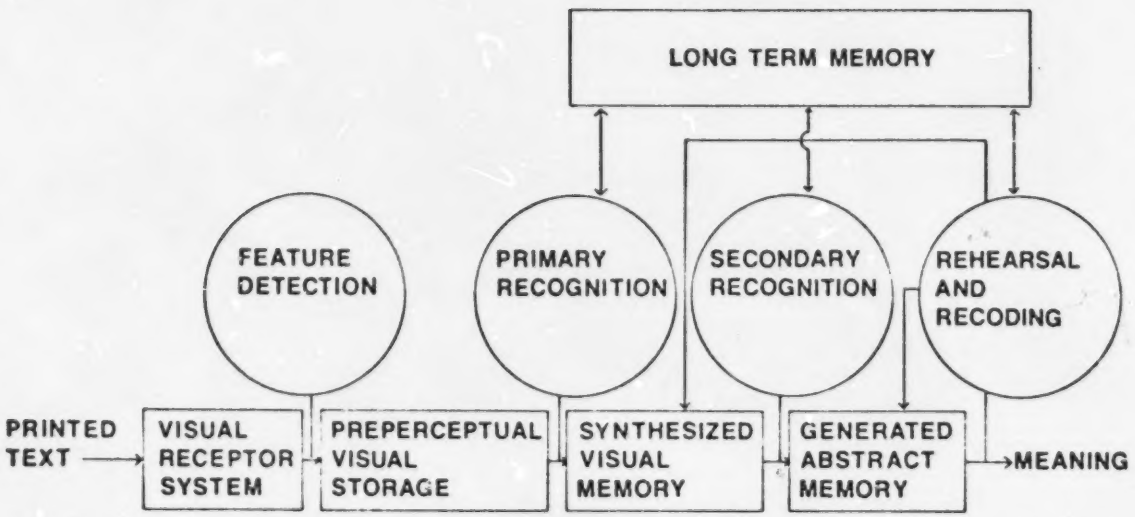

Figure 1. An information-processing model of reading printed text.

accomplished reader includes a list of features for each letter of the alphabet along with information about the orthographic structure of the language. The primary recognition process evaluates the features in preperceptual visual storage and compares or matches these features to perceptual prototypes in long-term memory. A perceptual prototype represents each of the letters as it would ideally be represented in preperceptual visual storage. The primary recognition process seeks for each letter position the perceptual prototype that provides the best match to the featural information in preperceptual visual storage. This process operates on a number of letters simultaneously (in parallel). Featural information is resolved by feature detection at different rates and there is some evidence that gross features are available before more detailed features (Breitmeyer & Ganz, 1976; Massaro & Schmuller, 1975). The primary recognition process is therefore faced with a succession of partial information states. These may be regarded as yielding candidate sets of letters that are successively more consistent with the available featural information for each letter position in the string being synthesized. The reduction of these candidate sets to a single best matching letter (or to no match) relies not only upon the incoming visual features but also by a knowledge of orthographic structure. If, for example, an initial th has been resolved in a letter string, and the features available for the next letter are consistent with either c or e, the process might synthesize e without waiting for further visual information, since initial thc is not acceptable while initial the is. Conversely, the actual presence of an irregular string or substring such as thq might demand more exhaustive featural information for acceptance of each of the three letters because of the illegality of the sequence. It is assumed that

the two sources of information, visual features and orthographic structure knowledge, make independent contributions to the recognition process (Massaro, 1973, 1975, in press a; Thompson & Massaro, 1973). In this view, orthographic context facilitates word perception, but it does not modify the feature analysis of the printed pattern (Massaro, in press, a).

The primary recognition process transmits a sequence of recognized letters to synthesized visual memory. Figure 1 shows that the secondary recognition process transforms this synthesized visual percept into a meaningful form in generated abstract memory. We assume that synthesized visual memory holds a sequence of letters that are analyzed by the secondary recognition process with the goal of resolving the letter string into a meaningful word. The secondary recognition process makes this transformation by finding the best match between the letter string and a word in the long-term lexicon. Each word in the lexicon possesses both perceptual and conceptual codes. The word recognized is the one whose perceptual code gives the best match as well as whose conceptual code is most appropriate in that particular context.

Generated abstract memory corresponds to the short-term or working memory of most information processing models. In our model, this memory is common to both speech perception and reading. Recoding and rehearsal processes build and maintain semantic and syntactic structures at the level of generated abstract memory. It is also possible to go in the opposite direction in the model, from meaning to a visual or auditory percept. The recoding operation can transform the meaning of a concept into its surface structure and auditory or visual form.

In this model, one role of orthographic structure in word recognition

is to facilitate the primary recognition of individual letters. It is well-known that orthographic structure functions at later stages of processing, such as facilitating rehearsal and recoding. Baddeley (1964), for example, showed that a well-structured string of letters is easier to remember and recall than a random string. Regardless of the potential for facilitation at other stages, however, the important effects of orthographic structure on perceptual recognition seem well established (Massaro et al., (Note 1): Massaro et al., 1979; Taylor, Miller, & Juola, 1977). We have chosen to concentrate our attention on these effects.

Reading Difficulty

Given the information-processing model, an important issue is determining the stage or stages of processing responsible for reading difficulty. It is likely that different stages of processing might be critical at different levels of reading development. In the present model, deficits could exist in either the temporary processing stages, in the long-term knowledge base, or both. Feature detection, primary recognition, secondary recognition, and rehearsal-recoding stages might each be responsible for various reading difficulties. We will consider each of these possibilities.

Feature Detection

Feature detection differences between good and poor readers would locate the latter's deficit at a nonlinguistic visual level. Poor readers might simply have acuity problems or insensitive or malfunctioning feature detectors. Acuity and sensitivity problems have been generally found to be minor and easily remedied causes of poor reading. Malfunctioning feature detectors would present a less easily corrected deficit and could

be responsible for the classic symptom of dyslexia (Orton, 1925). For example, normalization functions of higher-order detectors might malfunction giving the appearance of letter reversals or rendering certain discriminations extremely difficult. It is unlikely that low-level visual processing differences can account for differences in reading skill, however. Jackson and McClelland (1975) found no differences between good and poor readers in a tachistoscopic recognition of a foveally presented letter or two peripheral and spatially-separated letters.

Primary Recognition

Good and poor readers may differ in their ability to integrate the featural information in preperceptual storage, in their utilization of orthographic structure, or both. Mason and Katz (1976, Experiment 2) assessed these possibilities with sixth grade readers. The good readers were reading at about grade 9 level, whereas the poor readers were reading at about grade 3, based on Science Research Associates Achievement Series scores. Rather than using actual letters as test stimuli, Mason and Katz used 12 Greek and other symbols from an IBM typewriter symbol ball. Performance on a no-redundancy condition was compared to a redundancy condition in a target search task. On each trial, a target symbol was presented followed by a test string of six symbols; subjects indicated whether or not the target symbol was present in the test string. In the no-redundancy condition, any of the 12 symbols was equally likely to occur in any of the 6 positions in the test string. In the redundancy condition, only two symbols could occur in the first position, two different symbols in the second position. The fifth and sixth positions were similarly limited. The other remaining four symbols could occur only in positions three and four. These constraints roughly approximate

six-letter English words in which constraints are greater at the beginning and end than at the middle.

In the no-redundancy condition, reaction times did not differ for the good and poor readers. This result means that the good and poor readers did not differ in their ability to evaluate and integrate the visual featural information of the test string in order to perform the target search task.

Good and poor readers did differ in the redundancy condition, however, in that good readers benefited from redundancy whereas poor readers did not. Reaction times for good readers were significantly faster in the redundancy than in the no-redundancy condition; reaction times for poor readers were equivalent in the two conditions. This result indicates that good but not poor readers utilized higher-order structure (redundancy) at the primary recognition stage of processing. Generalization of the result to normal reading implies that good readers utilize orthographic structure at the primary recognition stage of reading better than poor readers.

Secondary Recognition

Secondary recognition transforms the visual experience of print into a higher-order abstract code. The code is called abstract because it no longer maintains the visual quality of the information stored in synthesized visual memory. The outcome of secondary recognition is meaning and usually a corresponding verbal code to be stored in generated abstract memory. The meaning code does not have to be lexical but could simply be representations of the phonemic, syllabic, or morphological distinctions of the language. Naming a letter-pattern or any visual pattern requires the transformation of the visual experience into the appropriate higher-order code.

Recently, a number of investigators have proposed that differences in reading skill are in good part due to differences in readers' ability to translate printed patterns into the appropriate higher-order verbal codes (Hogaboam & Perfetti, 1978). In a thorough series of experiments, Perfetti, Finger, and Hogaboam (1978) tested third graders and found that less skilled readers do not differ from skilled readers in naming colors, digits, and pictures but are much slower to name words. Given that a picture and its corresponding word represent the same object and are, therefore, given the same name, the differences cannot be due to just ability to retrieve and articulate the appropriate name. The critical component of the deficit appears to be transforming a printed representation to a higher-order representation. The deficit could be at either or both primary and secondary recognition stages in our model. It is interesting that even for the good readers, words were not named significantly faster than pictures. A consistent finding is that adults name words much faster than they name their corresponding pictures (Potter & Faulconer, 1975). Comparing absolute reaction times across the two studies, it appears that the time to name words decreases dramatically with reading experience whereas the time to name pictures remains relatively constant. Third graders can name pictures in roughly a second and college students are only about 10% faster. For words, unskilled third grade readers require 400 msec more than their skilled colleages and 800 more than college students. Experience facilitates naming printed words much more than naming pictures.

Jackson and McClelland (1979) found that the speed of accessing memory codes for visually presented letters correlated strongly with reading ability in college students. Reading ability was measured in terms of

effective reading speed computed from overall reading speed and comprehension. Fast and average readers were presented with two letters, one upper-case and one lower-case, and indicated whether or not the letters had the same name. Fast readers were 78 msec faster than average readers in this task. In contrast, fast and average readers showed no differences in the times needed to indicate whether two random dot patterns were the same or different. Since the comparison in the first task requires accessing name codes whereas the comparison in the second task must be carried out at the visual level, it appears that one difference between the two groups of readers is the speed of accessing letter codes in memory.

Rehearsal-recoding

Vellutino (1977), in a review of the literature, organized evidence to support the idea that poor readers do not verbally code and store information as efficiently as average readers. Many of the previous findings of reader differences in intersensory integration and temporal-order perception appear due to rehearsal-recoding processes. Vellutino and his colleagues (Vellutino, Steger, & Kandel, 1972; Vellutino, Smith, Steger, & Karman, 1975) have shown that poor readers can visually reproduce short words even though they cannot pronounce them. Liberman and her colleagues (Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1976) have shown that superior eight-year-old readers exploit a speech code in generated abstract memory to a greater degree than poor or marginal eight-year-old readers. In one experiment, confusable (rhyming) letters were much more difficult to remember than nonconfusable letters for good than for poor readers. Jackson and McClelland (1975) found that fast readers

had a larger span of apprehension than their average colleagues, as measured by a report of unrelated letters. These results support the idea that reader differences may be correlated with the efficiency of rehearsal and recoding at the level of generated abstract memory.

Long-term Knowledge, Verbal Ability, and Awareness

Almost by definition, long-term knowledge and verbal ability correlate with reading ability. Reading test performance is highly dependent on what the reader already knows and the verbal skills that have been developed. Jackson and McClelland (1979) found that reading ability was most highly correlated with listening comprehension. Better readers were also more accurate in verbal and quantitative reasoning tests. Furthermore, it is sometimes possible to perform at an acceptable level on a reading test without even reading the material. These results emphasize the caveat that reading skill cannot be assessed and treated independently of other information-processing and cognitive skills.

Rozin and Gleitman (1977), Mattingly (1972), and Valtin (Note 2) have articulated a strong case for the importance of linguistic awareness in reading and learning to read. Rozin and Gleitman (1977) argue that one source of problems in learning to read an alphabetic language is that the alphabet is tied to phonemes not always directly represented in the sounds of the words themselves. Valtin (Note 2) views phoneme learning not as a perceptual discrimination task but as a cognitive task in which the phoneme categories are viewed as phonetically arbitrary classifications. Liberman et al. (1977) found that kindergarten children showing the greatest difficulty in phonemic segmentation of spoken words also had the greatest difficulty in learning to read. If the child does not have

access to the phonology of the language, more elaborate recoding and rehearsal processes might not be possible.

Orthographic Structure

Although Anderson and Dearborn in their comprehensive 1952 book, The Psychology of Teaching Reading, acknowledge the effects of familiarity and set on word perception, the utilization of orthographic structure is not addressed. Nowhere do the authors explicitly recognize that the perception of some letters can provide information about other letters or that some letters are more likely to occur in some positions and contexts than others. Familiarity and set effects were assumed to occur at the word level or even higher at the phrase or sentence level, but not at the sublexical level. One of the first studies of the utilization of orthographic constraints in reading was carried out by Miller, Bruner, and Postman (1954). These authors had subjects reproduce letter sequences flashed in a tachistoscope. The eight-letter strings corresponded to different approximations to English based on Shannon's (1948, 1951) algorithms. The authors found that performance improved with increases in the degree to which the letter strings approximated English. By correcting for the statistical redundancy in the strings, the amount of information transmitted was shown to be equal for the various approximations. This result is consistent with more recent empirical and theoretical work demonstrating that orthographic structure provides an independent source of information to the reader (Massaro, in press, a). Massaro (in press, b) provides a review of how orthographic structure facilitates reading and Massaro et al. (Note 1) discuss various descriptions of orthographic structure in English.

To assess how good and poor readers utilize knowledge about the structure of written language, it is necessary to state various descriptions of this structure and then determine how well these descriptions capture reading performance. Venezky and Massaro (in press) and Massaro et al. (1979) have distinguished between two broad categories of orthographic structure: statistical redundancy and rule-governed regularity. The first category includes all descriptions derived solely from the frequency of letters and letter sequences in written texts. The second category includes all descriptions derived from the phonological constraints in English, scribal conventions for sequencing letters in words, or both. Massaro et al. (1979) contrasted a specific statistical-redundancy description with a specific rule-governed description in a series of experiments utilizing a target-search task. The statistical-redundancy description was the summed single-letter positional frequencies of the letters in the test string. This summed frequency measure was derived from counts which give the number of occurrences of each letter by word position and word length in a sample of written text (Mayzner & Tresselt, 1965). For test strings of six letters, the frequency measures would be the sum of the frequency of the string's first letter as the first letter in six-letter words plus the second letter's frequency as the second letter in six-letter words, etc. Although the rule-governed description was not as systematically developed, a set of rules was formulated to classify strings as orthographically regular or irregular. The selection rules are given in Appendix 1.

To create the test stimuli Massaro et al. (1979) chose six-letter words and made anagrams of each of them to find four strings that

orthogonally combined high and low single letter positional frequency and regular and irregular orthographic structure. This 2 x 2 factorial design provides a direct assessment of the contribution of frequency and regularity to letter perception. Mason (1975) had previously evaluated the contribution of summed single letter positional frequency in a letter search task. Good and poor readers indicated whether or not a six-letter string contained a predetermined target letter. In one experiment (Mason, 1975, Experiment 2), good readers averaged 63 msec faster for strings high in positional frequency than for those low in positional frequency. Massaro et al. (1979) were concerned with two primary issues raised by Mason's results. First, we questioned whether a frequency measure of orthographic structure was sufficient to describe the facilitating effects of structure on perceptual recognition when a rule-governed description of orthographic structure may also be important. Second, Mason's results appeared highly variable. We questioned whether the target search task revealed large effects of orthographic structure. There were a number of reasons to suspect the robustness of Mason's effects. Subjects had only 5 practice trials and just 72 experimental trials. With one third of these trials devoted to words, there were only 24 trials per subject for each of the two experimental nonword conditions. For the 12 good readers this constituted only 288 observations, minus errors, contributing to each experimental condition. Mason found that 100 practice trials in a followup experiment reduced the performance advantage for high positional frequency strings to an average of about 22 msec. Additionally, Mason found differences in the strength of this positional frequency effect between target present trials and target absent, or catch, trials. Mason attempted

to argue that summed positional frequency is more important on target trials than on catch trials, but she did not offer a convincing reason why this should be the case. A good model of the utilization of orthographic structure must account for performance on both target and catch trials.

In the target search task of Massaro et al. (1979), good sixth grade readers were asked to indicate whether or not a target letter was present in a six-letter string. Each trial began with the presentation of the target letter, followed 800 msec later by the test letter string. The test letter string was shown until the subject responded. The subject was instructed to respond YES if the target letter appeared at least once in the letter string and NO otherwise, and the subject was told to respond as accurately as possible. The subject was tested once on each of 320 unique stimuli, giving roughly 80 observations per subject for each of the four experimental conditions (less error trials).

Figure 2 gives the results from the initial experiment. Although the reaction times were about 12 msec faster for regular than for irregular strings and about 12 msec faster for high than for low positional frequency, neither result was statistically significant. These results confirmed our suspicion about Mason's study and made apparent two alternative interpretations. First, positional frequency and regularity may not contribute significantly to perceptual recognition in the target search task. Perhaps our manipulation of positional frequency and regularity did not capture the knowledge source that the subject utilizes in perceptual recognition. A second possibility is that our manipulations varied psychologically important dimensions of orthographic structure,

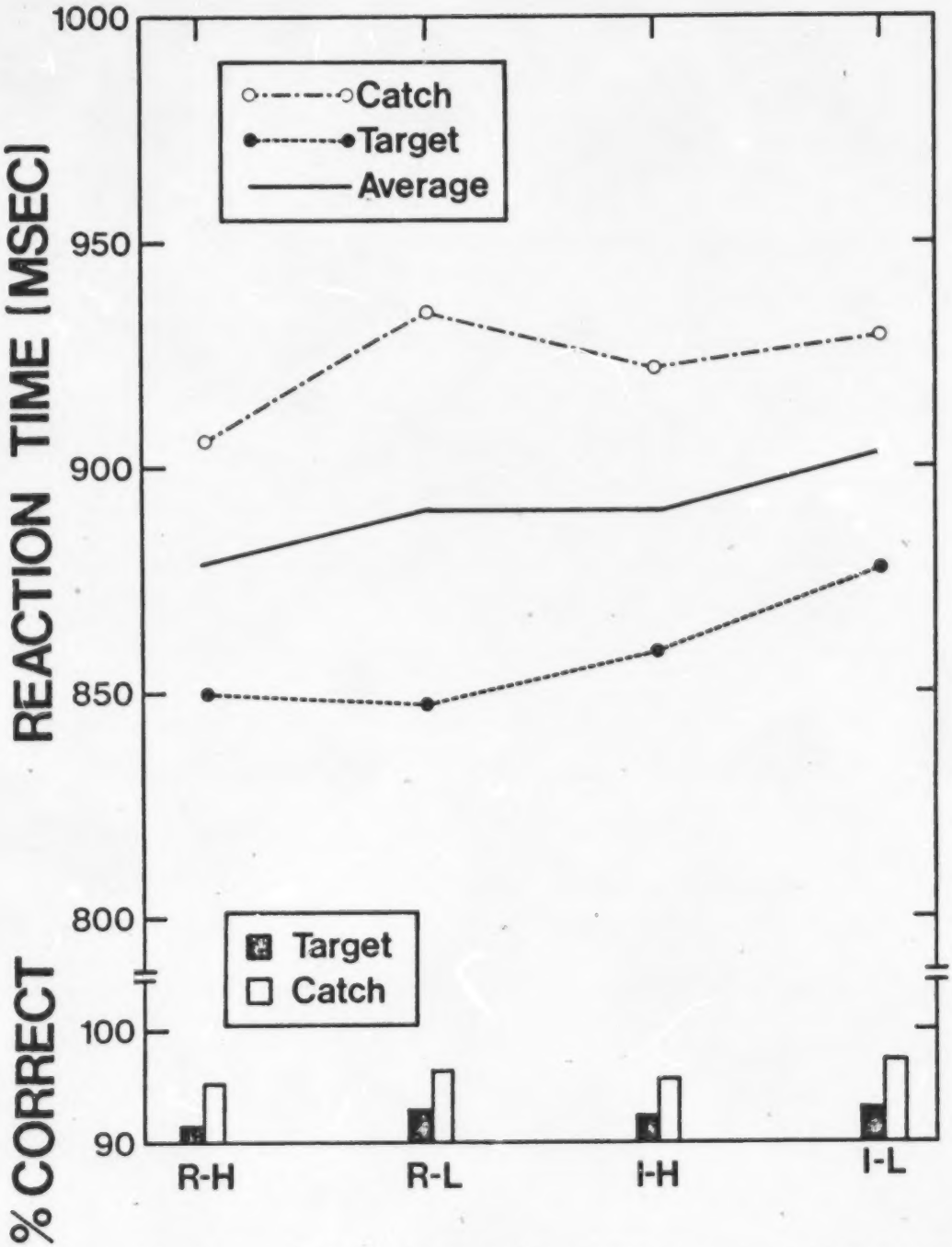

Figure 2. Reaction times and percentage correct responses as a function of regularity and positional frequency for target and catch trials in the target search task (after Massaro, Venezky, & Taylor, 1979).

but reaction times in the target search task are too insensitive to the crucial stages of perceptual recognition.

Our interest in this issue led us to conduct an extensive sequence of experiments contrasting reaction time tasks with accuracy tasks. The results of this research are reported in Massaro et al. (1979) and Massaro et al. (Note 1). The most salient finding for the present experiment was that both precued and postcued accuracy tasks reveal strong effects of orthographic structure. The accuracy results were also found to correlate highly with measures based upon frequency counts and rule-governed regularity.

Although these experiments have answered most of the questions raised in our minds by Mason's (1975) study, they did not incorporate the variable of reading ability. The present research uses the powerful accuracy tasks to probe whether individuals of varying reading ability use orthographic structure differently.

The two experiments reported here are direct replications of the Massaro et al. (1979) accuracy task with a new set of items and the inclusion of corresponding word stimuli. Figure 3 illustrates the five types of items used in the experiments. College sophomores having good reading scores were contrasted with peers having poor reading scores in the first experiment. Sixth graders at three reading levels and adults comprised the four groups in the second experiment.

Experiment 1

Method

Subjects. A class of 248 college students in Introductory Psychol-

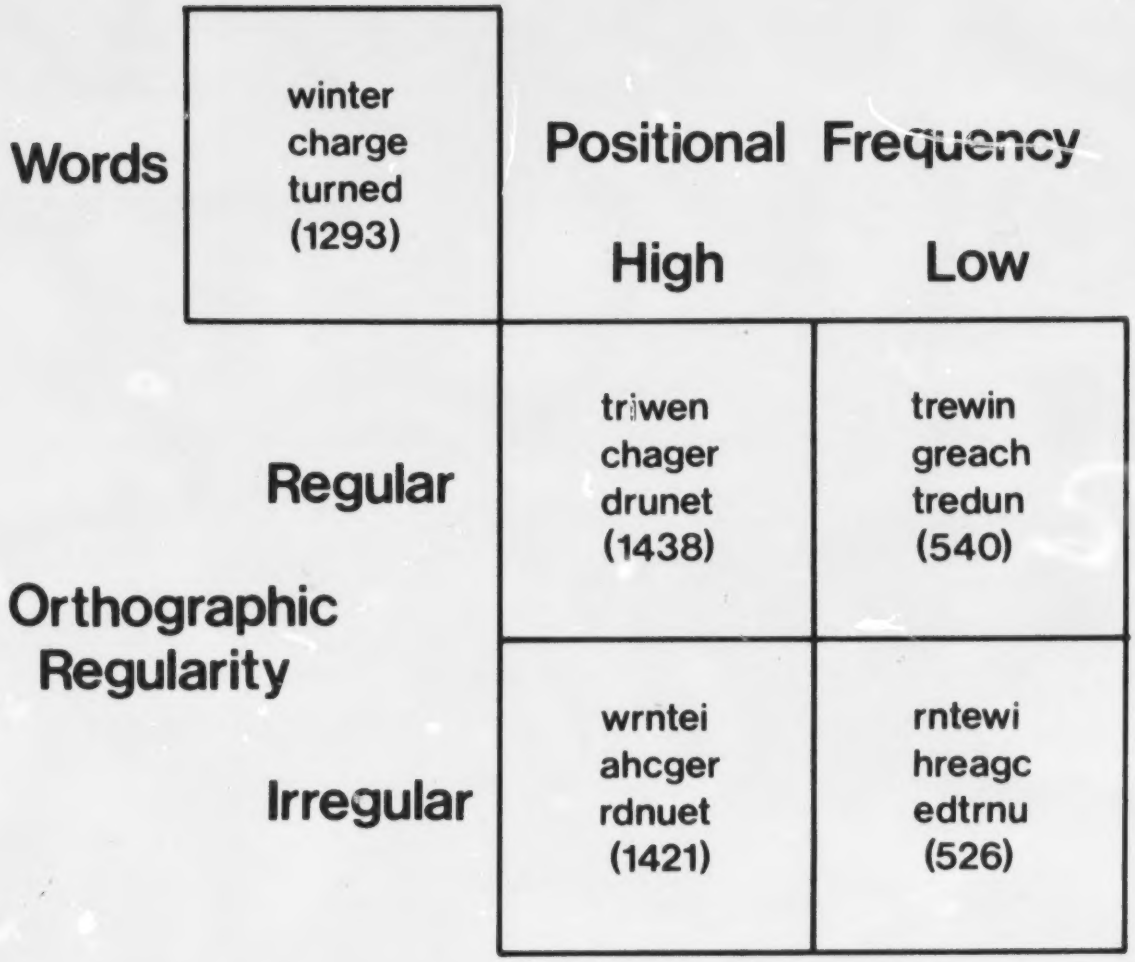

Figure 3. The five types of items and examples of each type used in the experiments. The number in each cell is the average summed single letter positional frequency for that item type.

ogy was given the Nelson-Denny reading test (Forms C & D, 1973) under the "Cut-Time Administration" limits for adults. These limits permit 7½ minutes for the 100 vocabulary items and 15 minutes for the 72 comprehension questions. The resulting distribution of student scores closely paralleled the standard norms for this administration procedure with a mean score for our sample of 80.9 and a standard deviation of 21.8. Students scoring in the top 15% (raw scores of 106 to 140) and the bottom 15% (raw scores 60 to 17) of our sample were selected as our "good reader" and "poor reader" populations, respectively. Of these two groups, 19 good readers and 15 poor readers agreed to participate in the experiment and were paid $2.00 for their participation. Of these 34 subjects, 16 good readers and 11 poor readers achieved experimental accuracy scores between 60% and 80%. Five of these good readers were randomly excluded to maintain equal group sizes. Thus, 11 good readers and 11 poor readers formed the final subject groups. The mean raw reading score for the final good reader group was 113.5 and the mean for the poor reader group was 50.3.

Stimulus List. Listings of the 100 highest and 100 lowest positional frequency anagrams were obtained for several hundred common six-letter words selected from the Kucera and Francis (1967) word list. The anagram listings were produced by a computer program which generated all 720 possible permutations for each six-letter word and computed the positional frequency for each permutation from the Mayzner and Tresselt (1965) single-letter counts for six-letter words by summing the position dependent frequency for each letter. Words with repeated letters were not used. From the 200 anagrams for each six-letter word, two were chosen

with high positional frequencies and two were chosen with low positional frequencies. Within each frequency pair, one member was chosen to be orthographically irregular and one to be orthographically regular. The rules used for judging regularity are listed in Appendix 1. Appendix 2 lists these 200 stimulus items--the 40 words and the four anagrams of each word. From 24 additional words, 120 practice stimuli were generated. These words were not as evenly matched for regularity and positional frequency as the experimental words and a few contained repeated letters.

Two occurrences of each of the 120 practice stimuli were presented in random order for each subject's practice sequence and two occurrences of each of the 200 experimental stimuli were presented in random order for each subject's experimental sequence. In the two occurrences of each stimulus, one occurrence was tested as a target trial and one as a catch trial. On target trials, the target letter was selected randomly from among the six letters in the test string. For catch trials, a target was selected randomly from a set of 21 letters weighted by their probability of occurrence in the stimulus set. If the selected letter was present in the display string, additional drawings with replacement were made until an appropriate target letter was selected. The letters j, k, q, x, and z did not occur in the experimental stimulus strings and, therefore, were never tested.

Apparatus. The visual displays were generated by a DEC LSI-11 computer under software control and presented on Tektronix Monitor 604 oscilloscopes (Taylor, Klitzke, & Massaro, 1978a, 1978b). These monitors employ a P31 phosphor with a decay to .1% of stimulated luminance within 32 msec. The alphabet consisted of lower case sans-serif letters

resembling the type font Univers 55. For an observer seated comfortably at an experimental station, the six-letter displays subtended about 1.9 degrees of visual angle horizontally and the distance from the top of an ascender to the bottom of a descender was about .4 degrees. This computerized laboratory facility permitted testing up to four subjects in parallel. Each subject received the same visual display on the display monitor, and the computer collected individual subjects' responses.

Procedure. A trial began with the presentation of a single point in the center of the screen which served as a fixation point. After 250 msec the fixation point was replaced by the test string followed after a variable blank interval by the masking stimulus. The masking stimulus was made up of a montage of random letter features. The mask changed from trial to trial and covered the exact area of the test stimulus on that trial. The fixation point returned, followed by the target letter. The onset of the masking stimulus always occurred 70 msec after the onset of the test string and the onset of the target letter always occurred 180 msec after the onset of the masking stimulus. The target letter remained present until all subjects responded or for a maximum of 4 sec. The intertrial interval between the offset of the target letter and the onset of the fixation point was 500 msec.

The durations of the test strings and masking stimuli were adjusted in order to keep average performance as close as possible to 75% correct. The target duration could vary between 10 and 39 msec and the mask duration could vary between 1 and 30 msec. The summed duration of the target and mask was always 40 msec and the durations were traded off using an adaptive algorithm. The durations were modified after every block of 20

trials during which time each trial type (target or catch) by display type (word, R-H, R-L, I-H, I-L) occurred exactly twice. Therefore, all conditions were tested an equal number of times under the same stimulus conditions.

Each subject was tested on a single day for about 90 minutes. The testing session consisted of 120 practice trials, and two 400-trial experimental sessions. Subjects were given rest and feedback after the practice trials and a rest period between the two experimental sessions.

Results

Figure 4 presents the average percentage of correct responses as a function of the five display types; reader ability is the curve parameter. There was an overall 26% difference across display types, $F(4,80) = 169$, $p < .001$, but this difference was identical for good and poor readers, $F(4,80) = .37$. Responses were 13% more accurate for words than for regular-high items, 9% more accurate for regular than for irregular items, and 4% more accurate for high frequency than for low frequency items. These results replicate other studies with these items (Massaro et al., Note 1) and show absolutely no effect of reading ability on the role of orthographic structure.

Although the role of orthographic structure did not change with reading ability, good and poor readers were influenced differently by the type of trial. Figure 5 plots performance accuracy of good and poor readers for target and catch trials as a function of display type. Good readers were about equally accurate on target and catch trials whereas poor readers averaged 20% better on catch than on target trials, $F(1,20) = 5.87$, $p < .025$. The advantage of catch over target trials for poor

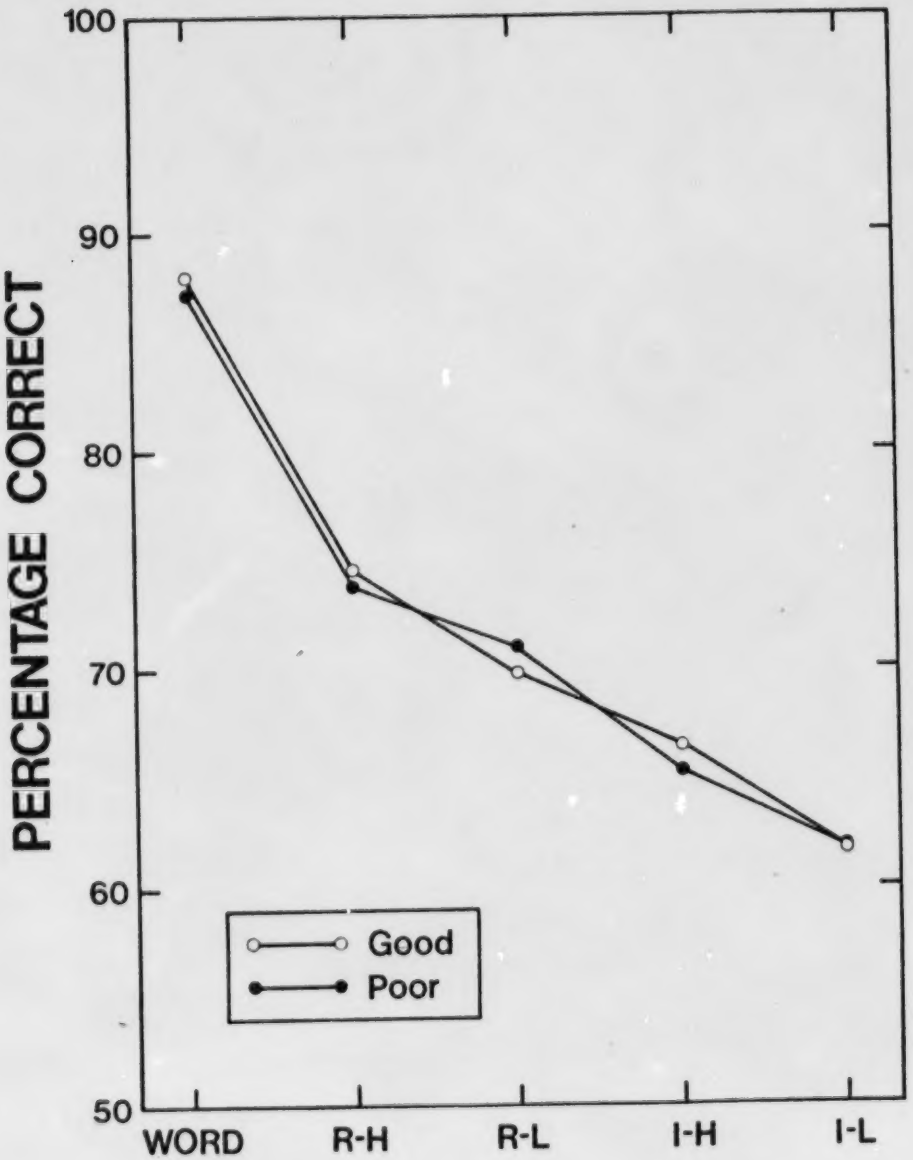

Figure 4. Percentage of correct responses for college readers as a function of the orthographic structure of the test string; reading ability is the curve parameter (Experiment 1).

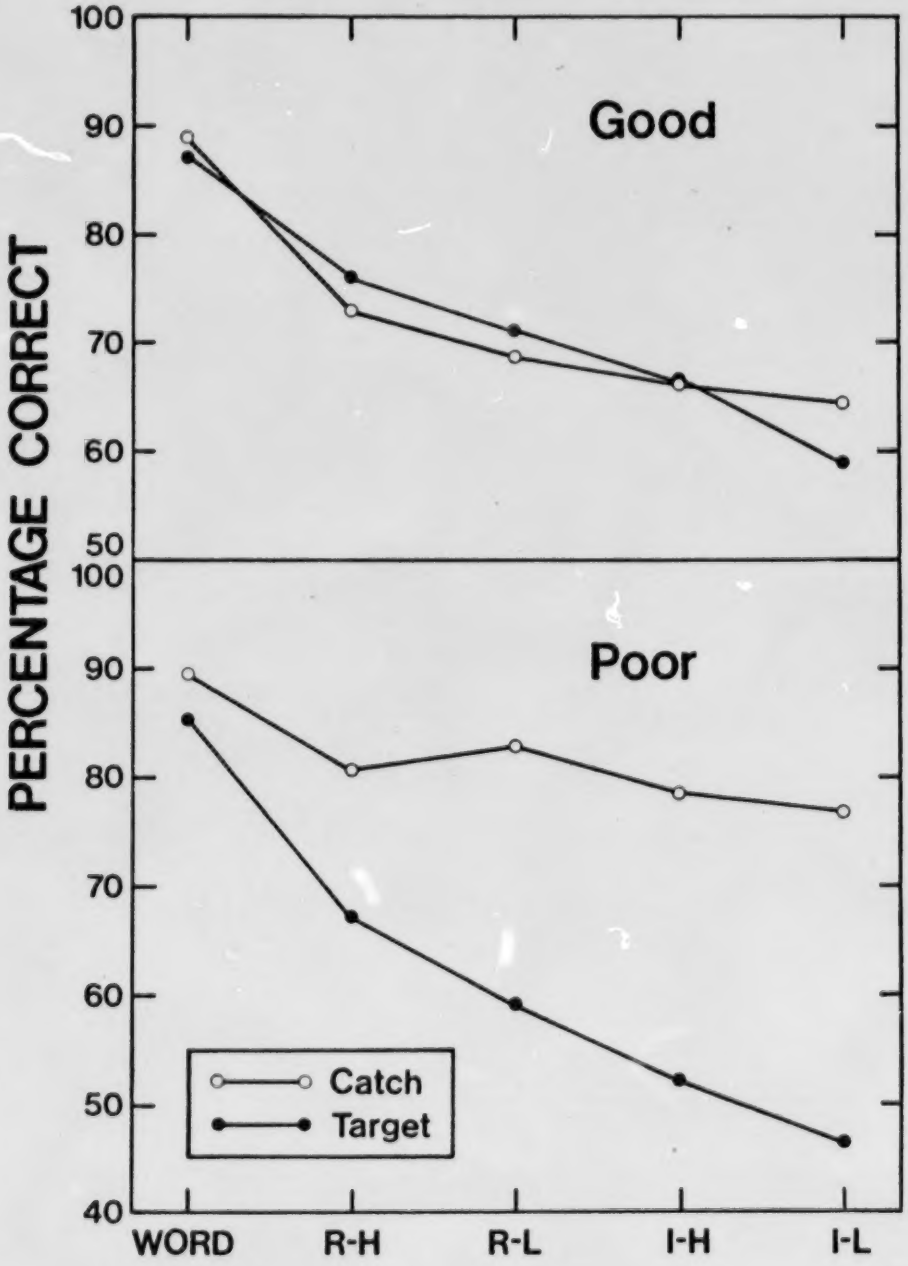

Figure 5. Percentage of correct responses on target and catch trials for good and poor college readers as a function of orthographic structure of the test string (Experiment 1).

readers increased as the orthographic structure of the displays decreased, $F(4,80) = 3.97$, $p < .01$. This result may reflect a conservative bias for poor readers. Given incomplete visual information, poor readers may be more reluctant to say that they saw a target letter even though their evidence is just as good as that for good readers.

Experiment 2

Method

Subjects. The subjects were 42 sixth graders selected from the Madison Public Schools and 14 college students in Introductory Psychology who volunteered to participate for extra class credit. The sixth graders who administered the comprehension subtest of the Gates-MacGinite Reading Test (1965, Survey D, Form 1). Comprehension grade level scores varied from grade 3.5 (raw score of 19) to 11.9+ (perfect score of 52) with an average of 7.2. These students were ranked on comprehension score and divided into three equal groups. The mean comprehension grade level for the groups was 5.0, 7.8 and 11.9, respectively. The sixth graders ranged in chronological age from 11.6 to 13.3 with a mean of 12.1. The mean chronological age for each of the three groups was within .1 year of the overall mean. All participants, sixth graders and adults, were paid $5.00 for participation.

Stimuli and Apparatus. The test displays and apparatus were identical to those in Experiment 1.

Procedure. The procedure was identical in all respects to that in Experiment 1 except that the target letter was given before rather than after the test display. Each trial began with a fixation point for 250 msec, followed by a target letter for 500 msec followed by the test dis-

play and masking stimulus. The fixation point then replaced the masking stimulus and remained on until all subjects responded or for a maximum of 4 sec. The next trial began after an intertrial interval of 500 msec. The durations of the test and masking stimuli were adjusted in the same manner as in Experiment 1.

The sixth graders were given the twenty minute reading test prior to the experimental test session; the adults received only the test session. The testing session consisted of 120 practice trials and two 200-trial experimental sessions. Subjects were given rest and feedback after the practice trials and a rest period between the two experimental sessions. The complete experiment took about 90 minutes for the sixth graders and 60 minutes for the adults.

Results

Figure 6 plots the percentage of correct responses as a function of orthographic structure for each of the four groups of readers. Performance improved an average of 10% with increasing orthographic structure, $F(4,208) = 44$, $p < .001$, and the magnitude of increase was not significantly related to reading ability, $F(12,208) = 1.2$, $p > .2$. Although the interaction of reading ability and orthographic structure was not statistically significant, the effects of structure were 16% for adults, 10% for the good and average sixth graders and only 6% for the poor sixth grade readers. The high variability within each group must be responsible for the nonsignificant effects. Table 1 gives the range of the orthographic structure effects for the subjects within each of the four groups of readers. The orthographic structure effect for each subject was determined by subtracting the irregular-low score from the

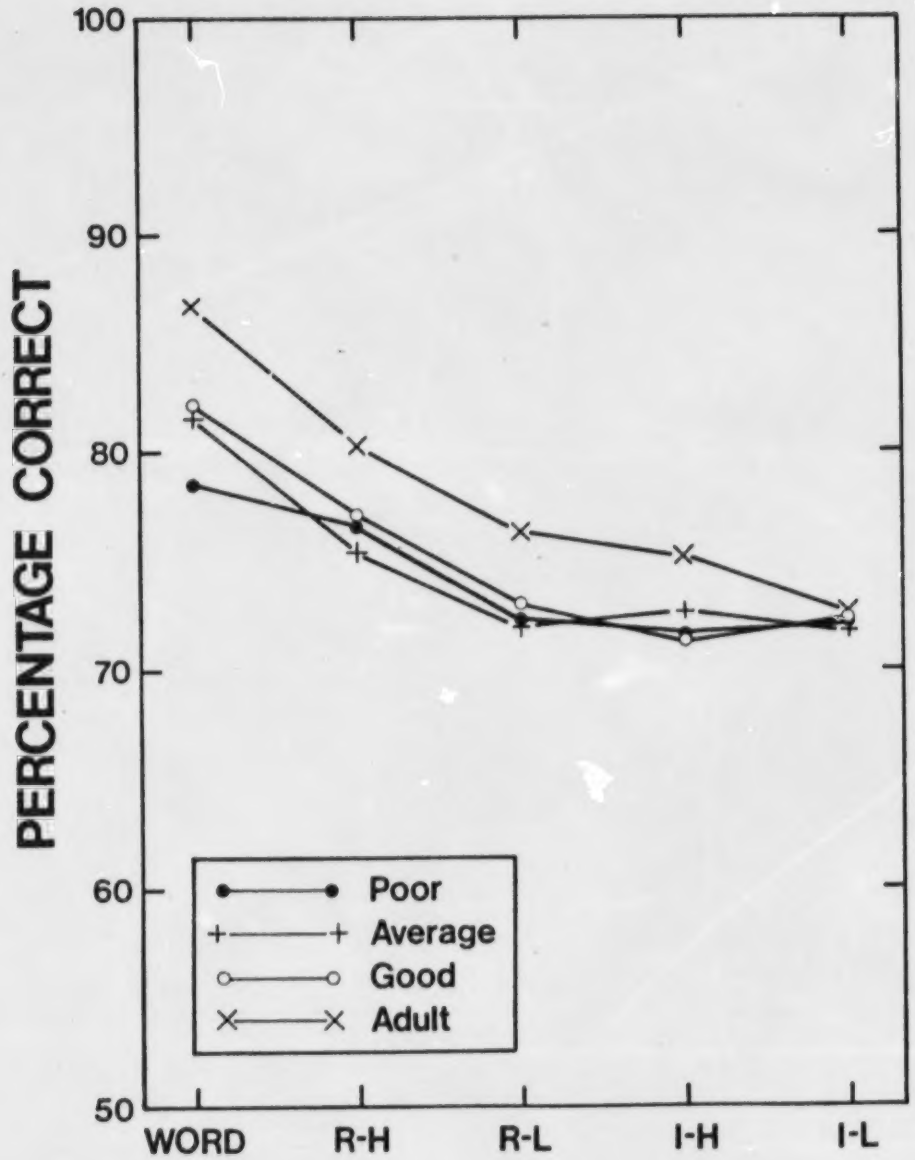

Figure 6. Percentage of correct responses for good, average, and poor sixth grade readers and for adult readers as a function of orthographic structure of the test string (Experiment 2).

Table 1

Mean and Range of Orthographic Structure Effects as a Function of Reader Group

	Mean	Range
Poor sixth graders	6.4	-2.5 to 15.0
Average sixth graders	9.8	-5.0 to 18.75
Good sixth graders	9.8	-4.7 to 22.5
Adults	16.2	-1.25 to 27.5

word score. Unfortunately, the data are highly variable within each of the four groups. It appears that 400 total trials or 80 trials per display type are not sufficient for statistically reliable data.

Overall, subjects were about 7% more accurate on target than on catch trials, $F(1,52) = 20.5$, $p < .001$, but this result did not interact with reader ability, $F(3,52) = .91$. The advantage of target over catch trials also increased about 3% with decreases in orthographic structure, $F(4,208) = 2.7$, $p < .05$, and this effect was not significantly related to reader ability, $F(12,208) = .58$.

Correlation Analyses

Massaro et al. (Note 1) have correlated a number of frequency measures and one measure of regularity with performance on the 200 items used in the present experiments. The source of all of the frequency measures is a word corpus sampled by Kucera and Francis (1967). Counts were determined for single letter, bigram, and trigram units. Tables were prepared by counting the occurrence of each unit by position in words of a given length. Massaro et al. (Note 1) give the details of the preparation of the tables. The single letter positional frequency of a given letter in the test string is measured by the frequency with which the letter occurs in the same serial position in words of six letters. The summed single letter frequency of the complete letter string is the sum of the positional frequencies of each of the individual letters in the string. Summed bigram and trigram frequencies are analogously defined in terms of bigram and trigram letter combinations. Position-insensitive counts give the cumulative frequencies of the units without regard to position in words of six letters.

All unit frequencies were based on word token rather than type counts. A type count counts each particular word only once regardless of how often it occurs whereas a token count counts the number of occurrences of each word. The two counts are highly correlated in the English language. Each position-sensitive frequency of a given unit was transformed to a logarithmic value before the summed counts for the letter strings were computed. Massaro et al. (Note 1) and the present study found that these log counts correlated more highly with the performance measures than did the linear frequency counts.

The word frequency counts were taken directly from the Kucera and Francis (1967) count. Log word frequencies were used in the correlations since these correlated higher than linear word frequency. The value 0 was assigned to all nonwords.

Finally, as an attempt to quantify regularity, Massaro et al. (Note 1) computed a simple count of orthographic irregularities for the 200 test items. An irregularity was counted for each impermissible vowel cluster as well as for each phonologically illegal consonant cluster when considered as part of a monosyllable. The counts were made negative so that the expected correlations would be positive. The exact rules for the irregularity count are given in Massaro et al. (Note 1).

Table 2 gives the correlations of the predictor variables with overall accuracy performance as a function of reading level in Experiments 1 and 2. Position-sensitive summed trigram counts provide the overall best predictor of performance. All of the predictor variables are correlated with performance to some degree and what is true for one measure is generally true for the others. The predictor variables are

Table 2

Correlations of a Number of Predictor Variables with Overall Accuracy Performance as a Function of Reading Level in Experiments 1 and 2.

	Experiment 1			Experiment 2		
Predictor	Good	Poor	Adults	Good	Medium	Poor
Position-sensitive frequency						
single letter	.513	.492	.366	.223	.175	.195
bigram	.671	.678	.487	.400	.254	.283
trigram	.704	.720	.477	.458	.350	.280
Position-insensitive frequency						
single letter	.203	.229	.165	.128	.020	.106
bigram	.520	.543	.374	.337	.199	.242
trigram	.644	.645	.406	.411	.293	.258
Word frequency	.601	.634	.381	.324	.327	.226
Regularity	.514	.508	.332	.266	.186	.247

Note: With 199 df, correlations greater than .18 are significant at $p < .01$.

significantly correlated with each other. For example, the correlation of word frequency with performance can be completely accounted for by trigram frequency. Word frequency and position-sensitive trigram frequency correlated .78 in the present list of letter strings.

For the postcue task in Experiment 1 position-sensitive summed trigram frequency measures account for about 50% of the variance in overall accuracy on each of the 200 test items. Consistent with the main effects in the factorial design, the correlation did not differ for good and poor adult readers. The large correlations found in Experiment 1 were significantly attenuated in the precue task of Experiment 2. For adult readers, the best predictors now account for only 23% of the variance. However, the correlations now vary systematically with reading level. For example, position-sensitive summed trigram counts range from .48 for the adult readers to .46, .35, and .28 for the good, medium, and poor sixth grade readers, respectively. Therefore, the reading level differences found in the factorial analyses in Experiment 2 are also apparent in the correlational analyses.

Discussion

The orthographic structure effects were significantly smaller in the precue task of Experiment 2 than in the postcue task of Experiment 1. The 26% difference across item types for the college sophomores was reduced to a 16% difference. This result is consistent with the idea that the target letter precue may encourage the reader to rely less on knowledge about orthographic structure. Rather than attempting to resolve the letter string into a word or wordlike string, the subject may simply look for critical features of the target letter. Massaro et al. (1979) and

Massaro et al. (Note 1) present some evidence in favor of this interpretation. The effects of orthographic structure appeared larger in a postcue accuracy task than in the precue reaction time task. The overall reduction in the importance of orthographic structure in Experiment 2 may be partly responsible for the relatively small effects of reader ability. It is possible that reader ability would play a much more important role if a postcue task were used with younger readers.

The results of these two studies do not discourage our belief that the utilization of orthographic structure is an important component of reading performance. Although good and poor college readers may utilize orthographic structure to similar degrees in the target search task, the poor readers may have spent more time and effort in mastering the use of this structure in reading. If this is the case, it is not surprising that deficits exist at other important processing stages for poor readers.

Although poor college readers utilized orthographic structure as well as good readers in the target search task, poor readers might not utilize orthographic structure to the same degree in normal reading. If selective attention plays an important role in reading (LaBerge & Samuels, 1974), then differences between good and poor readers might be a function of whether or not selective attention is possible. Poor readers might utilize orthographic structure only when selective attention is possible; good readers might do so with or without selective attention. The target search task allows selective attention to visual processing since higher-order comprehension processes are not required. In a typical reading situation, however, it would be detrimental to selectively attend to visual processing and disrupt higher-order comprehension processes. One

test of this idea would be to require additional higher-order semantic/syntactic processing during the target search task. Subjects could be asked to shadow spoken prose during the task or to determine whether or not spoken sentences are sensible (Kleiman, 1975). If the utilization of orthographic structure requires selective attention for poor but not for good readers, then an additional higher-order processing task might be sufficient for finding differential orthographic structure effects for poor and good readers. We plan to test this idea in the near future.

Given the fact that reading ability was important to the experimental task at the sixth grade level, it might play an even larger role for younger readers. If reading ability is more dependent on visual processing skills for younger than for older readers, it should then be a better predictor of orthographic structure effects in the target search task. We plan to test third graders in the target search task to assess the extent to which orthographic structure effects are a function of reading ability.

Classroom Practice

The psychologically real description of orthographic structure has yet to be isolated although its existence as a psychological construct has been established. It may not be premature to discuss some implications of the present research for learning to read. If the utilization of orthographic structure in word recognition is an important component in reading, then it may be profitable to facilitate the child's understanding of this structure. Children should be able to learn some of the constraints in English orthography at about the same time that they usually learn phonics. Instead of drill and practice, a game format

could be employed to teach various orthographic structures. In this section, we present only a few possible games since teachers will probably prefer to develop their own variations. We also present some of the important constraints in written English that could be profitably taught. Although these constraints are based on letter occurrences in written text for adults (Kucera & Francis, 1967), we plan in the near future to measure written text for grades 3 to 9 (Carroll, Davies, & Richman, 1971). It remains to be determined whether orthographic constraints remain relatively constant for texts across reading levels.

The goal of the games is to teach children common letter patterns and where in words these patterns are most likely found. Before describing some of the games, we will present some of the important constraints in English orthography. These constraints will serve as the learning material in the games.

One of the most noticeable constraints in English orthography is the difference between where consonants and vowels occur in words. Vowel sounds are relatively infrequent in initial or final position in English words. Therefore, the reader can expect words to begin and end with consonants, except for final e which is not pronounced. For example, when the letters a, e, i, o, u, and y occur in five-letter words, they occur in first position only 9% of the time. The letters a, i, o, and u are found in final position in five-letter words on only 1% of their occurrences. If the orthography were unstructured, then the expected occurrence at one of the five positions would be 20%. Therefore, since most words contain at least one vowel, vowel letters can be expected more often in the medial positions than in the initial and final

positions (except for e and y which are relatively frequent in final position; when these two letters occur in five-letter words, they occur 35% of the time in final position). The digraph vowels, ea, ee, ie, oa, and oo also occur most often in medial positions. Similarly, in short words which are usually monosyllabic, consonants are more likely to be found in initial and final positions.

Overall, constraints in English orthography are greatest at the beginning and ends of words. Syllable boundaries in the middle of words permit almost any letter or pair of letters to occur in medial positions. It is possible to compute the constraints as a function of position in words by deriving a measure of redundancy or predictability for each serial position. The variance of letter occurrences at each serial position was computed based on the tables of frequencies derived from the Kucera and Francis' (1967) counts. A high variance occurs at a particular position to the extent some letters occur more often than others at this position. As might be expected from phonological and scribal constraints, letters are much more predictable in initial and final positions than in the middle of six-letter words.

In terms of information content, word recognition from the ends inward would be an optimal strategy. Luckily, orthographic constraints occur at exactly those letter positions which also have better visual information. It is well known that letters at the beginning and end of letter strings are perceived more accurately because they have only one letter neighbor rather than two. Lateral masking occurs when an adjacent letter lowers the perceptibility of its neighbor and the first and last letters in a string suffer less lateral masking than those in the middle.

In normal reading, the medial letters would not benefit from higher acuity because of a more foveal placement since the word is not necessarily fixated in the middle. The higher information content and better visual information in initial and final letters could lead to earlier recognition of initial and final letters in a word string. This partial information may then be sufficient for lexical access.

Consonant clusters are another key feature of English orthography. There are great constraints on the frequency and location of these clusters in English words. Table 3 presents the most frequently occurring bigram consonant clusters in initial and final position in English words of four through seven letters. The clusters th, st, and ch are frequent in both initial and final positions. The cluster sh occurs about four times more often in initial than in final positions. However, all other clusters frequent in one position are relatively infrequent or actually illegal and nonoccurring in the other. Of the 20 frequent consonant clusters in initial position, 13 of them do not occur at all in final position. Three others (sp, sc, and sm) seldom occur in final position. Of the 20 frequent consonant clusters in final position, 14 of them never occur in initial position. Three others (ll, ts, and gh) only occur a few times and might be considered illegal in initial position. In this way, there is extremely high predictability with regard to where most consonant clusters can be found in English words.

The implications of the fact that many consonant clusters in initial and final positions are illegal if the letters are reversed in order are interesting. All of the initial consonant clusters in Table 3 are illegal if the letters are reversed. The clusters th and wh are frequent in

Table 3

The Most Frequently Occurring Consonant Clusters in Word-Initial and Word-Final Positions in English Words of Four Through Seven Letters

	Word-Initial	Word-Final
1.	th	ng
2.	wh	th
3.	st	st
4.	fr	ch
5.	sh	ld
6.	pr	ll
7.	ch	nd
8.	gr	nt
9.	tr	rs
10.	pl	ts
11.	cl	ht
12.	sp	ds
13.	br	ss
14.	kn	ck
15.	dr	rt
16.	sc	rd
17.	cr	ns
18.	bl	gh
19.	sm	ct
20.	fl	ls

initial position but ht and hw cannot occur in initial position. Similarly, many of the clusters in final position are illegal and do not occur when the letter order is reversed. This constraint could nicely compensate for a potential visual difficulty in reading. There is some evidence that readers may correctly recognize the letters in a string but mistake their relative positions. These transposition errors have been observed in experiments by Estes, Allmeyer, and Reder (1976) and others. Transpositions of letters have even been proposed as one of the primary causes of dyslexia--the child reading the word <u>was</u> as <u>saw</u> (Orton, 1925). Utilization of the constraints on letter clusters could conceivably compensate for difficulty in resolving the relative spatial position of letters. A reader having resolved the letters c and h would know they must occur in the order ch and not in the order hc. Similarly, the vowel clusters ea and oa can be clarified upon recognition of the letters since ae and ao seldom occur in English.

Given these constraints in English orthography, what games can be played to familiarize the reader with these constraints? One possible game is very similar to the experiments presented here. Students could be asked to search for letters and letter clusters in common English words. It is not necessary (and, in fact, not desirable) that all of the words be in the child's written vocabulary. Students could be given a vertical list of words and asked to search the list from the top down checking each word that contains a particular letter or cluster of letters. A stop watch could be used to measure the search time and some score could be given in terms of the number of letters found and the search time. Following the game the children can discuss where they have found

certain letters and clusters and what general rules of thumb might be helpful. The benefits of learning the rules should be readily apparent to the children. Knowing that the consonant cluster wh must occur at the beginning of a word would greatly facilitate searching a list of words for this cluster. The word lists could be varied to stress the particular constraints being taught.

This game could be used to teach many of the constraints we have discussed. The differences between vowels and consonants, the common consonant and vowel clusters, the positions in which letters and letter clusters are usually found, and the unique ordering of the letters in most clusters can be illuminated in the target search task.

A second set of games is a simple adaptation and extension of games used in phonics instruction. Kohl (1973) describes a toy consisting of three pentagon-shaped blocks arranged along a wooden peg. Each block can be turned to expose each of the five sides. It is possible to put letters and letter clusters on each side to form a wide variety of spellings. The left block would have only consonant and consonant clusters legal in initial positions, the middle block would have vowel and vowel clusters, and the final block would have only consonant and consonant clusters legal in final position. Turning these three blocks separately can produce 125 unique and legal English spellings. Of course, not all of the spellings will be words, but the child will be learning sublexical constraints. Another practical implementation of this game would be to make a lazy susan with three circles differing in size but joined together at the center. The letter patterns can be written on each of the three circles; rotating them independently would produce all possible combinations.

Letter strings can also be created by arranging and rearranging a small number of letters and letter clusters on a magnetic board. Here the game could be made more interesting by having the children create new words to describe certain events. The goal would be to create the word visually rather than orally although the child could also attempt to pronounce the new word during or after it is spelled.

Finally, the student could be asked to categorize letter strings as possible or impossible sequences. If the string is called impossible, the student could further indicate what is wrong with it and how it might be corrected.

Obviously, this is not a comprehensive list of games and we are confident that teachers will want to develop others. Initial reactions of reading teachers have been very enthusiastic. It is generally accepted that children should be made increasingly aware of language, and although orthographic structure is just one small attribute of written language, it will be to a student's advantage to understand and utilize this structure in reading and writing.

Footnotes

The paper was written while Dominic W. Massaro was at the University of California, Santa Cruz and Glen A. Taylor at Texas A&M. Glen A. Taylor is now at Bell Laboratories, Homdel, New Jersey.

David Klitzke programmed the experiments, assisted in testing the subjects, and contributed to the data analyses. Peter Lucas and Jim Jastrzembski also helped out in the data analyses. The ABC statement is taken from a print by Donald M. Anderson.

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Appendix 1

Rules for the Selection of Orthographically Regular and Irregular Strings

From the list of permutations of a real word for a particular summed positional frequency class (high or low), a string was selected for the orthographically irregular list if it contained any of the following spellings:

a. phonologically illegal (in English) initial or final cluster (e.g., tlfies, iastlr).

b. orthographically illegal spelling for an initial or final consonant or consonant cluster (e.g., hreagc, tlerav).

c. an illegal vowel spelling (e.g., prsaed, nmtaou).

d. a phonologically illegal medial cluster (e.g., ilmpes, irltsa).

Regular strings were selected to be (a) phonologically legal, and (b) to contain common vowel and consonant spellings. These rules were derived by extending the rules given in Venezky (1970), Venezky and Massaro (in press), and Massaro et al. (1979).

Appendix 2

The word, regular high (R-H), regular low (R-L), irregular high (I-H), and irregular low (I-L) strings used in Experiments 1 and 2.

Words	R-H	R-L	I-H	I-L
action	cainot	onicat	aiocnt	icntoa
amount	mauton	otanum	auotnm	nmtaou
answer	swaner	erswan	wnraes	rnwesa
barely	blayer	byeral	lbraey	rbleya
belong	goblen	glenob	lnboeg	ebgnlo
breath	thaber	therab	bhrtea	rtbeha
bridge	begrid	gredib	ierbgd	ebrgdi
charge	chager	greach	ahcger	hreagc
double	bodule	edolub	leoubd	obdeul
famous	foamus	osafum	uaomfs	ofmsua
finger	fering	grefin	rfnieg	efngri
garden	nagred	gredan	arnged	ednrga
gather	thager	greath	hrtaeg	grheta
glance	caleng	glecan	lcnaeg	eclnga
hardly	hyrald	hydral	yrahld	rdlhya
itself	siflet	flesit	tlfies	eflsti
lawyer	weraly	lyeraw	rwlaey	eyrlwa
longer	logren	gleron	glnoer	egnrlo
master	tasmer	steram	mrtaes	emrtsa
modern	dormen	drenom	oermnd	rmedno

Appendix 2 (Continued)

Words	R-H	R-L	I-H	I-L
mother	thomer	therom	mroteh	hretmo
namely	manely	lyeman	lmnaey	emnyla
nearly	lareny	nyelar	lrnaey	enyrla
permit	primet	trepim	tmriep	rtpeim
player	rapley	lyerap	plraey	epylra
poetry	petory	tyerop	yptoer	erytpo
purely	yulper	ryelup	lpyuer	erplyu
reason	sarone	erosan	snaoer	rnseoa
remain	ramine	amerin	mraien	rniema
result	surtel	tresul	lrtues	elsrtu
shared	shread	dreash	srdaeh	hsreda
simple	pimsel	emslip	ilmpes	lsepmi
single	snigel	glesin	ilgnes	nglesi
spread	prased	dresap	prsaed	dsepra
stared	sarted	dresat	srtaed	dtsera
stream	trames	tresam	mtraes	esrtma
travel	vartle	treval	avrlet	tlerav
trials	sartil	trisal	iastlr	irltsa
turned	drunet	tredun	rdnuet	edtrnu
winter	triwen	trewin	wrntei	rntewi